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ABSTRACTS OF PAPERS: JOINT MEETING OF AFOSR CONTRACTORS IN SOLID ROCKET COMBUSTION AND THE PANEL ON SOLID PROPELLANT COMBUSTION INSTABILITY

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Prepared for:

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STABILITY GRADING OF PROPELLANTS BY OSCILLATORY STRAND BURNER TEST

By

J. Diederichsen
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SUMMARY

It is not yet possible to make reliable predictions regarding the stability of combustion for new formulations of solid propellants. At R. P. E. Westcott an attempt is being made to develop a method for the determination of stability characteristics of propellants without the necessity of full scale motor firings. The method is based on the now generally accepted principle that oscillatory burning in a motor will be sustained or amplified only if the instantaneous rate of energy release in the region of pressure antinodes is significantly increased at the time when the pressure in these regions is within 1/4 cycle of its maximum.

The apparatus used at present consists of a 48 inch long steel tube of 2 inch diameter which has a window at the position where a propellant strand is mounted. The tube is pressurized to 1000 lb/sq. in. with nitrogen. Oscillations in the nitrogen are excited by means of a loud speaker unit at the frequency of that natural overtone in the nitrogen which produces a pressure antinode at the position of the propellant.

The variation in light output from the burning propellant is taken as a measure of the variation of the instantaneous rate of reaction. The light output and the pressure are recorded. So far two double base propellants have been burnt in the apparatus. It was found that the oscillations in the light output for these two propellants were approximately 1 and 0.05% respectively of the total light output when the pressure amplitude was 5 lb/sq. in. at a frequency of 2400 cycles/sec. The pressure oscillation and the light oscillation were nearly in phase.

It is intended to extend these measurements, using a range of frequencies and pressure amplitudes, to examine a variety of propellants, and to correlate the results with motor firings.

Abstract

Progress Report on Measurement of Surface Impedance of Burning Solid Propellant

R. S. Stern and A. O. Converse
Thiokol Chemical Corporation

In the work at Thiokol-Elkton an attempt is being made to measure the surface impedance of burning solid propellant by means of a technique developed by O. K. Mawardi to measure the surface impedance of inert acoustic materials. As a first stop, measurements of the impedance of acoustically-damping materials at atmospheric pressure were made. The results are reasonable, but it is impossible to compare our results with those of Mawardi because the materials that he used are no longer manufactured. Unfortunately, the conditions used by other experimenters have been different than in our experiments. Our samples have been shipped to A. B. L. for comparative testing, however. Next, the apparatus was modified to permit the use of a burning material at high static pressures, 500-2000 psi. At present we are at the point where experiments on burning propellants can be started.

ABSTRACT

DECOMPOSITION, COMBUSTION AND DETONATION OF SOLIDS

D.J. SIBBETT, F.J. CHESELSKE, I. GELLER, J.M. LOBATO, J.E. SUTHERLAND AND R.F. CHAIKEN

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The objectives of this work are to obtain better understandings of the mechanisms of decomposition, combustion and detonation of solids. During the past year work has been carried on in four areas: (1) mechanisms of surface decomposition processes, (2) reactions in the defect solid, (3) kinetics of gas phase processes associated with the combustion of composite solid propellants and (4) kinetics of processes occurring in the detonation reaction zone of solid explosives.

The decomposition of perchloric acid has been studied as the first of three prototype reactions which may occur in the gas phase above a decomposing surface of ammonium perchlorate. Between 150 and 260°C, the reaction appears to take place in the following steps:

$$2\ HClO_4 \xrightarrow{k_2} Cl_2 + 7/2\ O_2 + H_2O$$

$$HClO_4 + H_2O \longrightarrow HClO_4 \cdot H_2O$$

$$HClO_4 \cdot H_2O \xrightarrow{k_1} 1/2\ Cl_2 + 3/2\ H_2O + 7/4\ O_2$$

Rate constants for the second order reaction, k_2 and the first order reaction, k_1 have been computed from the initial and final data which was obtained by following the rate of pressure change. A computer solution of the simultaneous differential equations which represent the reaction scheme demonstrated that the observed pressure may be computed when the two rate constants are evaluated. A product distribution has been calculated as a function of time. Chlorine pressures determined by a photoelectric colorimeter compared very closely with the computed values. Activation energies of the second order and first order steps were 8.9 and 21.3 kcal/mole respectively. Both reactions were shown to be surface catalyzed with a linear dependence of the two rate constants on surface to volume ratio at 200°C.

Initial experiments which are aimed at flame strength measurements on the diffusion flame between ammonia and perchloric acid gas have been carried out at pressures up to 1 mm. Despite a hot wire igniter system, stable flames have not yet been obtained. Apparatus for these experiments is described.

Work on high explosives has been concerned with an examination of the processes which may be rate-controlling during detonation. Hot-plate linear pyrolysis measurement have been made using compressed strands of TNT, RDX, PETN and Tetryl in an effort to determine whether vaporization is the rate limiting process in application of the Eyring grain burning detonation theory. Arrhenius plots of these data indicate that the surface decomposition process at temperatures just above the melting points of these materials is probably controlled by vaporization. Extrapolations of these data to detonation conditions demonstrate that detonation reaction times which result from these data are in reasonable agreement with Nozzle and Curved-Front computations for Tetryl, PETN and RDX. Experimental results from the linear regression data on TNT indicate shorter reaction times than are indicated by theoretical computations. Surface regression at temperatures well above the melting points of these materials (> 50°C) appears to be controlled by a viscous flow process. Discussion of the Eyring relationship between the temperature coefficient of viscosity and the heat of vaporization as applied to the case of TNT is included.

Entropy Waves Produced at a Burning Solid Propellant Surface under Oscillatory Pressure

by

Martin Summerfield and R. H. W. Waesche
Princeton University

Abstract of Talk to be Presented at
The Combustion Instability Conference
Palo Alto, Calif., March 7-9, 1962

In connection with theoretical considerations of the connection between the burning rate response function of a burning solid propellant and the acoustic admittance of the surface, it was concluded that at low frequency the product gas is emitted isothermally rather than isentropically as heretofore assumed, and it was observed that this necessitates a change in the relationship between the burning rate response function and the acoustic admittance.

At low frequency, (below 1000 cps), the emitted product gas carries a specific entropy that oscillates with time, producing entropy waves that are carried with the gas stream. These entropy waves are manifested by temperature waves (millimeters in length) that should be observable quite easily, and an experiment of this type is planned.

At higher frequencies (above 10,000 cps) a similar phenomenon should exist, that is, there should be entropy waves of strong magnitude. The modification of the formula for the acoustic admittance is more complicated, for several reasons. At such high frequencies, the entropy waves may be impossible to observe because of their very short wavelength. However, just as at low frequencies, the presence of entropy oscillations must modify the instability characteristics of a propellant.

This research was sponsored by USAF Office of Scientific Research, Propulsion Sciences Division, under a contract funded by the Advanced Research Projects Agency; additional support was provided by NASA for special investigation of certain low pressure phenomena.

Experimental Studies of Steady-State Burning of Solid Rocket Propellants

by

E.K. Bastress, D.W. Blair, R.B. Cole, A.J. Sabadell

J. Wenograd, K.P. Hall, M. Summerfield

Princeton University

Abstract of Talk to be Presented at

The Solid Propellant Conference

Palo Alto, California, March 7-9, 1962

This talk will summarize the findings of a number of separate researches conducted mainly as theses during the year since the last conference, and it will explain the objectives of the work now underway.

An experimental research that was directed at the determination of the role of particle size of perchlorate in the mechanism of burning of composite propellants brought out two major results. One is that the granular diffusion flame zone is dominated by mixing effects dependent on Reynolds Number and hence on particle size. The other is that the self-decomposition mechanism of ammonium perchlorate strongly affects the burning rate in the pressure range of 1000 psi and above. Satisfactory theoretical models for this range of pressures and above have yet to be devised.

Prompted by this finding, researches on burning rate above 1000 psi and up to 25,000 psi (in cooperation with the group under Dr. Picard at Picatinny Arsenal) are underway. The initial results confirm the unusual effects of ammonium perchlorate self-decomposition.

Research on the role of thermal radiation feedback from the flame zone to the burning surface has indicated that this cannot be neglected, especially at low pressures. The intensity of radiation is difficult to measure precisely, but it seems intense enough to demand modification of the theory and to justify observed scale effects on burning rate.

Current work includes photographic observation of flame zones and of the burning surface of the propellant during combustion; also, thermocouple surveys of the combustion zone are being made.

This research is sponsored by the US Navy Office of Naval Research, Power Branch, with funds provided by the Advanced Research Projects Agency. Supplementary support is provided by NASA to cover special studies in the low pressure range.

ABSTRACT

IGNITION OF COMPOSITE PROPELLANTS

Alva D. Baer and Norman W. Ryan
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The study of ignition was concerned with the response of propellant to an externally supplied heat flux. Both convective flux from shock-heated gas and black body radiant flux from electrically heated tube furnaces were employed. The convective flux tests gave results in good agreement with previously reported data. It was found that very high gas velocities produce an adverse effect on the ignition process. Also, oxygen in the gas phase appeared to have a decreasing effect on ignition as the gas velocity at the sample surface was increased.

The effects of radiant flux level, initial propellant temperature and pressure on the ignition process were studied in the radiation furnace tests. The theory of propellant ignition as a thermal process based upon the concept of a linear ignition criterion has been modified and extended. Both homogeneous and surface propellant ignition reactions are considered, and the theory is shown to quantitatively predict the effect of initial propellant temperature on the ignition time when the surface flux is maintained up to ignition. The experimental results confirm the theoretical predictions. The theory is non-commital with respect to the effect of pressure on ignition. Empirically it was found that the ignition times, t_i, of ammonium perchlorate propellants can be related to pressure, p, by the expression

$$t_i \propto p^{-n}$$

where the exponent n was from a 0.2 to 0.

As the surface fluxes were increased and ignition times reduced, the value of n decreased. For the high heat fluxes produced by conventional ignitions, ignition times are probably independent of pressure.

Theoretical and experimental studies of rarefaction tube operation have been made. Excellent agreement between theoretical predictions and experimental observations have been noted for low velocity gas flow in the rarefaction tube. An adequate technique for predicting rarefaction tube operation in the presence of significant frictional pressure drop has been devised.

Abstract

Current Research in Solid Propellant Ignition

E. F. Grant, C. E. Hermance, R. W. Lancaster, R. F. McAlevy III, K. P. Hall, J. Wenograd and M. Summerfield
Princeton University

This laboratory's earlier experimental research, which was conducted in a shock tube and led to the development of a gas phase ignition theory for composite propellants, has been extended to double-base propellants. The results show a strong effect due to oxygen in the igniting gas and indicate that a gas phase mechanism accounts for the ignition of these propellants also. In further experiments, the effects of a variety of oxidizing gases were surveyed. A number of such gases were found to effect a measurable but weak influence on propellant ignitability.

In the above experiments, conduction was the primary mode of heat transfer to the propellant surface. This limited the temperature to which the propellant surface could be heated and precluded ignitions in inert atmospheres in the available testing time. For this reason experiments were begun, using an existing large shock tunnel, which were designed to study ignitions on a flat plate with known temperature velocity and concentration gradients. Photographic studies of such ignitions have shown interesting but as yet inconclusive effects.

Another experiment has been developed at this laboratory for the study of ignition under conditions of convective heat transfer. In this device combustion gases from a small methane-oxygen rocket motor are allowed to flow through a small, cylindrically perforated, casebonded solid propellant grain. In this motor, the composition of the burnt gases, the mass flow, the solid rocket chamber pressure, and the flame temperature may all be controlled. In this manner, the ignition of the rocket grain may be studied under a variety of conditions. This work, still underway, has provided some interesting corroboration of the gas phase ignition theory.

The experimental results strongly support the idea that the gas phase ignition theory provides the basic mechanism by which a steady-state solid propellant flame is established. Further fundamental studies in this area should consider such questions as the nature of the participation of gases from the decomposing oxidizer and the precise description of the mechanism of the effect of igniter gas composition on the ignitability of solid propellants.

This research was supported in past years by AFOSR, Propulsion Sciences Division. Current research on ignition phenomena is supported by AFOSR under Grant AF62-91. Certain aspects of the work which pertain to low pressure conditions are given additional support under NASA Research Grant No. NsG-200-60.

ABSTRACT

Joint Meeting
Fourth Meeting AFOSR Contractors on Solid Propellant Combustion
Second Meeting Technical Panel on
Solid Propellant Combustion Instability

Radiative Ignition of Solid Propellants

Marjorie W. Evans, Stanford Research Institute
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The purpose of this work was to relate ignitibility, in a constant pressure system, to chemical kinetics of the solid phase, heat of reaction, thermal conductivity, heat capacity, transmissivity, and reflectivity. Ignitibility is defined in terms of level and duration of energy flux density required for ignition. Transmissivity and reflectivity were taken into consideration because the experimental method used a radiative source of energy. The material studied was ammonium perchlorate with and without the catalysts copper chromite and carbon.

A partial differential equation was stated relating these properties in terms of the dependent variable temperature of the solid and the independent variables time and one space coordinate, with boundary and initial conditions appropriate to the experiments. Experimentally determined values of the properties named (including chemical kinetics) were used in solving numerically the partial differential equation.

Consideration of the results of the solutions and the experiments leads to some conclusions regarding the roles and importance of solid phase exothermic and endothermic reactions, reactions of the solid which produce reactive gaseous products, and catalysts for these reactions. With respect to radiative ignition methods, conclusions as to the importance of reflectivity and transmissivity can be inferred.

ABSTRACT

The Catalyzed Decomposition of Ammonium Nitrate

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Various substances are known to catalyze the decomposition of solid propellant oxidizers. In the particular case of ammonium nitrate (AN), chromium compounds are unusually effective catalysts for decomposition of liquid ammonium nitrate. The heat release associated with the catalyzed decomposition may play an important role during ignition and the subsequent burning of ammonium nitrate propellants.

During the past year we have been studying the effect of chromium compounds on the decomposition of liquid AN. A complete reaction mechanism has not been obtained but the important overall features of the catalyzed reaction have been identified and will be discussed.

ABSTRACT

Combustion of
Laminar Solid Propellants

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The diffusion of a non-reacting gas injected through the permeable wall of a pipe through which another gas flowed turbulently, has been investigated, both theoretically and experimentally. Theoretical investigations started with the assumption of a "power-law" velocity profile, together with a consistent assumption of the eddy diffusivity of the gas. This led to using a universal velocity profile due to D. B. Spalding. With this profile and its associated distribution of eddy diffusivity near the pipe wall, the concentration distribution for the injected gas has been computed for a wide range of the dimensionless variables, but only for Schmidt numbers 0.7 and 1.0.

Concurrently with the theoretical investigations, an experimental check of the theory has been carried out using carbon dioxide injected into air. So far there is a discrepancy of order 40% between measured and theoretical distributions of the injected gas. If the discrepancy is cleared up, the result should be a theory permitting the calculation of concentration-distribution of an injected gas, for an arbitrary distribution of injection rate along the pipe wall in the axial direction. The analogous heat transfer problem will be soluble, too.

The Theory of Steady Burning of Composite Solid Propellants

W. Nachbar, Lockheed Missiles and Space Co.

ABSTRACT

The steady burning rate of the composite solid propellants that use ammonium perchlorate as oxidizer is now believed to be controlled by a number of mechanisms which interact with each other in a complex relationship. Among the chemical mechanisms are included the decomposition both of the solid binder (or fuel) and of the solid oxidizer, the gas-phase reactions involving the ammonium perchlorate decomposition products, and the gas-phase reactions between oxidizer and fuel. Mass diffusion of chemical species and the transport of thermal energy must also be considered. The burning rate is found to depend experimentally upon a number of variables, which include: pressure, weight fraction of oxidizer, size distribution of oxidizer particles, and variables describing the nature of the binder. The writer has previously proposed that at least the qualitative relationships can be studied theoretically by using a geometrically simpler mathematical model for which the burning rate would be rigorously steady. This is the sandwich composite model, composed of alternating slabs of oxidizer and binder. A realistic propellant weight fraction is chosen,and slab dimensions are of the order of mean oxidizer particle size. In our previous work, a solution for this model was obtained in analytic form for the limiting case where all gas-phase reaction rates are very much larger than the rates of mass diffusion of gaseous fuel and oxidizer.

Experimental investigations,by several groups,of the composite propellant burning rate as a function of the aforementioned variables leads to a tentative explanation of the effects of finite (i.e., pressure-dependent) chemical reaction rates upon the behavior both of composite solid propellants and of the sandwich composite model. The experimental data indicates that, for at least a portion of the range of variables, the monopropellant flame of ammonium perchlorate has a controlling influence on the burning rate of the composite propellant. The theory of monopropellant flames has been extensively studied under this contract (see AFOSR Document No. 2101, March 1962), and application of the theory has been made to correlate data on pure ammonium perchlorate deflagration (see AFOSR TN 60-700, August 1960). Agreement was satisfactory in this correlation with the exception of quantitative agreement on the magnitude of the low-pressure deflagration limit. Two changes in mechanism and their effect on the magnitude of the predicted deflagration limit are now described: (1) a postulated decrease in flame efficiency occurs as pressure decreases; and (2) a near-equilibrium surface condition, rather than the previously assumed rate law, occurs for lower burning rates. It is stressed that this question of the deflagration limit is possibly important for further theoretical studies of composite propellants, and that further experimental data on ammonium perchlorate appears necessary.

COMPOSITE SOLID PROPELLANT DEFLAGRATION STUDIES
BY MEANS OF A BURNER ANALOGY
BY
ROBERT F. McALEVY,III

The composite propellant deflagration process is being investigated experimentally on a fundamental level. A novel burner technique which realistically simulates in essential detail, both macroscopically and microscopically, the composite propellant flame zone is employed as the principal research tool. It permits ready experimental control of the factors which affect the propellant burning process, and over a wider range than can be produced in the propellants themselves. Further, it incorporates the means of experimentally controlling the rate at which selected propellant components enter the burning zone. Therefore the deflagration rate can now be studied as a function of component vaporisation rate since they are no longer fettered together by pyrolysis of the solid surface.

The burner deflagration rate will be measured as a function of a variety of chemical and physical factors (e.g. the chemical nature of the fuel and the oxidiser, pressure level, oxidizer particle size, temperature level, chemical additives, etc.) and then compared to the predictions of the prevalent theories of composite propellant deflagration rate, based on various assumptions concerning the structure of the flame zone. In this way it should be possible to discern which one of these approaches is most realistic for any given set of variables.

A presentation of the burner design philosophy, its construction and operation will be made. Preliminary results will be discussed.

ABSTRACT

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DETONATION CHARACTERISTICS OF LOW DENSITY GRANULAR MATERIALS

Marjorie W. Evans, Stanford Research Institute
Menlo Park, California

The purpose of this work, which is just beginning, is to study by analytical and experimental methods the detonation characteristics of low density granular materials. The objective is to devise a single, consistent model of detonation which will rationalize the variations of detonation velocity with diameter, failure diameter, and the shock sensitivity.

The analytical work will be concerned with (a) the mechanism by which a shock initiates a chemical reaction in a granular material and (b) incorporation of this mechanism and chemical kinetics into a von Neumann detonation wave. The experimental work will be concerned with measuring, for either ammonium perchlorate or PETN, or both, detonation velocity versus diameter, failure diameter, and shock sensitivity.

The Combustion of Elemental Boron

by

U. V. Henderson, Jr.
Texaco Experiment, Inc.

The reactions of massive elemental boron with oxygen, and with fluorine have been studied in order to determine the reaction mechanisms involved and their rate limiting steps. In the case of oxygen, the transport of oxygen to the boron surface is limited by the nature of the boron oxide at the temperature involved. At temperatures above 2200°K (the minimum temperature for self-sustaining combustion) the evaporation rate of the boron oxide is greater than its rate of formation and the rate limiting step is a gas phase diffusion of oxygen to the boron surface through boron oxide vapor. Evidence is also seen that indicates a two stage reaction with a suboxide being formed on the surface and the higher oxide formed in a gas phase reaction.

In contrast with oxygen, the reaction products of fluorine and boron are volatile at all temperatures studied and in adequate fluorine concentration the system is self-igniting, quickly reaching a combustion temperature greater than the melting point of boron (2300°K). Fluorination of boron in a mass spectrometer indicates that BF is the species evolved from the boron surface at rod temperatures from 800°K to 1650°K.

ABSTRACT

Atomic Radiation and Propellant Combustion

Speaker: Dr. Ernest J. Henley

Organization: Radiation Applications Incorporated
36-40 37th Street
Long Island City 1, New York

Atomic radiation offers a novel tool for elucidating certain aspects of the mechanism of solid rocket propellant combustion. Among the experiments which suggest themselves are:

1. Pre-irradiation of solid strand propellants -- this, in effect, results in the creation of a polymer structure having a controlled network.

2. Controlled radical generation -- focused electron beams are capable of generating radicals in a controlled volume, at a controlled rate.

In addition to experiments involving radiation, others in which free radical scavengers are injected into the gas and/or solid phase will be described.

Propellant systems of ammonium perchlorate with polystyrene asphalt and polyethylene were irradiated to doses of over 10 Megarads without effecting an initiation.

Specific Acoustic Admittance Measurements of Burning Solid Propellant Surfaces by a Resonant Tube Technique

Richard Strittmater
Leland Watermeier
Samuel Pfaff
Ballistic Research Laboratories

ABSTRACT

A resonant tube technique is used to measure the real part of the specific acoustic admittance of the active surface of a burning solid propellant. Measurements were made at mean pressures of 515 psi and in the frequency range of 3500 to 15000 cps. For ARP double base propellant, a value of 1.0 was obtained at 8200 cps for the quantity $\left[\frac{\mu}{\epsilon} - \frac{1}{\gamma}\right]$ of the Hart-McClure theory.

A single longitudinal mode is assumed in the analysis of data. That this is an acceptable approximation is confirmed by frequency analysis of taped pressure recordings.

The effect of sample thickness (thickness $<<$ quarter wave length) was investigated. Effects of the sample thickness on the experimental results are discussed. With this as a background, a minimum propellant thickness is suggested for experiments designed to measure the specific acoustic admittance of burning propellants.

ACOUSTIC WAVE-BURNING ZONE INTERACTION IN SOLID PROPELLANTS*

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Princeton, New Jersey

A system of determining the flame zone acoustic impedance of solid propellants burning at atmospheric pressure is described. In this system, acoustic energy from an acoustic driver is passed into one face of a disk of solid propellant, transmitted through the propellant, and radiated from the second face into an anechoic chamber. A microphone which is located in the anechoic chamber measures the amplitude of the radiated sound wave. When the second face of the propellant disk is ignited, the radiated sound wave passes through the flame zone, thence into the anechoic chamber. From a comparison of the effect of the flame zone upon the amplitude of the sound wave detected by the microphone, the acoustic impedance of the flame zone is deduced. Results to date will be presented.

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*This work is sponsored by the Office of Naval Research and the Advanced Research Projects Agency under Contract Nonr-3477(OO), ARPA Order No. 23-61.

ABSTRACT

Acoustic Admittance of Burning Solid Propellant Surface

G. M. Muller
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The possibility of measuring the normal acoustic admittance of a burning propellant surface by the reflected pulse method has been under investigation at Stanford Research Institute for about a year. This method involves sending a plane acoustic pulse down a long tube terminated by the surface to be investigated, and observing the pressure-time profile of the pulse before and after reflection. The harmonic components of the incident and reflected pulses are obtained by taking Fourier transforms; from these, the reflection coefficient and hence the admittance of the termination can be calculated on the assumption that the change in the pulse spectrum is entirely due to the termination. This assumption is not valid, however; there are additional changes due to non-linear and dissipative processes. In a previous report (Technical Operating Report No. 10 (June 30, 1961), Contract No. AF 49(638)-565, Project No. 4759) it was suggested that the true admittance of a given termination could be found by subtracting from its apparent admittance (which includes the effects of the unknown dissipative and non-linear processes in the tube) the apparent admittance obtained when the tube is terminated by a thick metal cap whose reflection coefficient is effectively unity. Recent experimental measurements of the acoustic admittance of a high-impedance sample (sandpaper cemented to an aluminum block) support the validity of the above theory. Measurements on the sample and on a plain aluminum block were obtained at two pressure levels, and although the apparent admittances of a given termination were quite different at the two levels, the true admittances obtained at each level agree quite well with each other over the range of frequencies for which the spectral density of the incident pulse lies within one-half of the maximum density. This range is approximately from 1250 to 2500 cycles.

EVALUATION OF A TRANSIENT METHOD FOR MEASURING ACOUSTIC IMPEDANCE

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R. B. LAWHEAD - ROCKETDYNE

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Contract AF49(638)-1093

ABSTRACT

The use of a shock tube technique for measuring acoustic impedance of burning solid-propellant surfaces is being studied. The pressure-time histories of weak shock waves incident on and reflected from a material under study are measured with high frequency response pressure transducers. Tests have been conducted at elevated pressures up to 500 psia to conviently obtain shocks with very small pressure rations. It is necessary to use shocks with pressure ratios less than 0.02 if wave broadening due to difference in propagation velocity of the head and tail of the shock is to be kept to a negligible value.

A complex reflection coefficient can be obtained from the measured pressure traces by defining the reflection coefficient as the ratio of the Fourier transform of the reflected pressure-time function to the transform of the incident pressure-time function. Experiments are being conducted to show that this transient reflection coefficient is identically equal to the classical acoustic reflection coefficient so that the impedance can be determined from the reflection coefficient using the conventional relationships between impedance and reflection coefficient.

Initial experimental tests with the transient method were carried out using an absorbing material (cellulose sponge) whose acoustic impedance was also measured using a conventional standing wave-travelling microphone technique. Agreement between the transient and steady-state measurements conducted to date have been relatively poor. It is suspected that much of the discrepancy may be due to non-linear behavior of the sponge under the very small but finite amplitude pressure (and velocity) variations associated with the shock. Tests are underway to further delineate these effects.

Exploratory tests were carried out using the transient experimental technique with burning solid-propellant samples in the shock tube at elevated pressures to determine the problem areas associated with the application of the technique to burning conditions. Large differences in the response to the shock excitations as measured with known "stable" and "unstable" propellants were clearly evident from inspection of the raw data.

Analysis of the data using the techniques which were suitable for the "col" tests was not possible due to complications introduced by the presence of a hot gas interface some distance from the propellant surface. The shock is found to reflect from this interface as a rarefaction wave which obscures the true wave shape of the reflection from the burning propellant surface. Placement of the pressure measuring station inside of the hot gas zone eliminates this problem, however, for this condition it is not possible to properly separate the incident and reflected wave so that their shape can be accurately determined. Alternate methods of analysis are being considered. One alternative is to determine the impedance of both the hot gas zone and the burning surface lumped together.

While this is a useful parameter for differentiation between stable and unstable propellants it is not the quantitative value of acoustic impedance required for use in the analytical description of solid propellant instability.

Abstract

Reflection and Scattering of Sound by Gaseous Flames*

by

H. M. WIGHT

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Aeronutronic Research Laboratories
Newport Beach, California

This report outlines details of a research program concerning investigation of reflection and scattering of relatively low intensity incident acoustic energy by gaseous flame fronts. The program - of combined experimental and theoretical nature - was initiated in October, 1961. The specific over-all objective is to determine under what conditions the total scattered acoustic energy might exceed the incident energy.

A description of the experimental equipment will be presented and also a brief survey of the relevant theoretical literature concerning wave scattering phenomena.

*This work supported by U.S. Air Force, Office of Scientific Research under Contract AF 49(638)-1106.

Some Experimental Observations of Aluminum Burning in Solid Rocket Propellants

Leland Watermeier
William Aungst
Samuel Pfaff
Ballistic Research Laboratories

ABSTRACT

Composite double-base rocket prope. ant slabs which contained different concentrations and particle sizes of aluminum were burned in a transparent-walled chamber. The slabs were ignited in cigarette fashion and burned under ambient nitrogen pressures of 200-800 psi. The chamber was exhausted to the atmosphere. Most of the experimental runs were made under steady flow conditions. In some runs, a siren rotating over the nozzle plate provided pressure waves normal to the burning surface at approximately 1100-1200 cps.

Motion pictures were taken of the burning process at high framing rates (2000-5000 pps). The histories of the burning aluminum droplets were followed by making measurements from individual and from successive frames of the film. Melting and agglomeration of aluminum on the surface with subsequent shedding of droplets into the flame zone was observed. The size and number of visible droplets in various zones above the surface were measured. Under steady chamber conditions, these droplets displayed major and minor axis oscillations whose frequencies varied, dependent upon diameter, from 500 to 1100 cps. The droplet diameter variations were often quite large. The mean diameter of the droplets tended to increase as they oscillated until they reached a particular distance above the burning surface. At this point, they started to decrease in diameter rapidly. This distance was decreased considerably under the influence of siren pulsing.

Drag forces were computed on the droplets and good correlation was found with observed variations in diameter and velocity.

Attempts were made to measure mass flux of the aluminum in the zones immediately above the burning surface. Although this was complicated by velocity and diameter variations, indications were that there is a significant aluminum mass flux variation in the 200-300 micron thick zone above the surface. It is postulated that the droplet diameter oscillations observed as well as any droplet number or mass flux variation in this zone would be a major contributor to low frequency instability observed in some highly aluminized propellants and would be of considerable significance in surface admittance.

ABSTRACT

Experimental Investigation of Finite Wave
Axial Combustion Instability

F. Jackson
Canadian Armament Research and Development Establishment

The CARDE program is aimed at an investigation of finite wave axial combustion in rocket engines with ammonium perchlorate/polyurethane propellants. In order to eliminate the statistical dependence of the occurence of instability, a pulse method of inducing axial instability in incipiently unstable engines has been developed.

For a fixed propellant, a series of engines of the same size is fired to determine the stability boundary in the K_n-D_p plane; the effects of scaling are being studied by firing engines of different diameters and lengths.

FLUID DYNAMIC MODEL FOR SOLID PROPELLANT COMBUSTION

T. Paul Torda, Armour Research Foundation

In the aerothermochemical analysis of the combustion in solid propellant rocket motors, the reaction chemistry (both solid and gaseous phase) of the propellant must be considered in conjunction with thermodynamics and fluid dynamics considerations. For purposes of analysis, it is expedient to consider two separate but mutually dependent zones within the combustion chamber. These are: (1) the solid surface and adjacent thin layer of gas wherein the major chemical phenomena and energy release occur (i. e., induction and combustion zones), and (2) the remainder of the combustion chamber in which fluid dynamic effects dominate (i. e., in the free stream or along the chamber axis).

A theoretical investigation of the phenomena occurring in zone 1 has been initiated with the inclusion of a longitudinal velocity. Thus far, an evaluation has been made of existing theories for both steady and unsteady combustion. The results of this evaluation are summarized. The pertinent conservation equations and associated boundary conditions have been derived and any assumptions are fully explained. Whereas previous investigations have neglected chemical reactions in the induction zone, it is felt that this might lead to an inaccurate prediction of temperature gradients, and therefore heat transfer, in this zone. An attempt is made to include chemical reactions by postulating a 2 species gas (reactants and products). By approximate methods a reaction rate law is determined. The limitations are recognized but the need for such chemistry is elaborated upon in the text. Viscous and diffusion effects are also included. The significance of this investigation is discussed in relation to the problem of oscillatory and unstable combustion in rocket engines.

Abstract

Current Experiments in Solid Propellant Combustion Instability

R. H. W. Waesche, J. Wenograd and M. Summerfield
Princeton University

The initial phase of a research program directed toward the determination of the response of a burning solid propellant to an oscillating pressure field involved the analytical evaluation of a limited number of suggested experiments. As a result of this survey, two of these experiments were deemed suitable for further investigation. One of these experiments involves the measurement of instantaneous gas velocities in the vicinity of the burning propellant surface by the tracking of luminous or illuminated particles; the other is based on the observation of the phase relation between pressure and luminosity or composition waves emitted by the propellant.

In order to conduct these experiments, it is necessary to have a source of high amplitude pressure oscillations. For this purpose a T-motor has been assembled and its operating characteristics defined. Preliminary experimental results are currently being evaluated.

The accuracy with which the particle track method will yield the acoustic admittance of the burning surface is a function of the particle drag. The motion of particles in an oscillating pressure field has been analyzed and limits for effective measurements established.

The postulated existence of composition or temperature waves and their pressure dependence have been studied using a film-strip obtained by Wood at Rohm and Haas. A phase relation was measured.

The research described in this paper was supported by the Propulsion Sciences Division of the Air Force Office of Scientific Research and Development with ARPA funds under Contract AF 49(368)-1073. Certain aspects of the work which pertain to low pressure conditions are given additional support under NASA Research Grant No. NsG-200-60.

SOLID PROPELLANT COMBUSTION INSTABILITY

R.D. Agosta, Polytechnic Institute Long Island Graduate Center

The approach assumed by the author in investigating solid Propellant Combustion Instability stresses the non-linear aspects of the gas-and-wave dynamics occurring in a rocket motor. The basic premise of the approach is to assume a mechanism that contains the characteristic behavior of the system, which can be realized both theoretically and experimentally. In addition, a reference standard, (e.g., the undisturbed state), is set-up so that any change of state can be unequivacally recognized.

A summary of the work to be presented will include: (1) Continuous wave coalescence in a non-gradient gas-dynamic field; (2) Continuous wave coalescence in a temperature-and-velocity gradient gas-dynamic field in the presence of mass addition, (evaporation, condensation) chemical reactions and drag; (3) Shock wave behavior in an arbitrary gas-dynamic field in the presence of mass addition (evaporation, condensation), chemical reactions and drag; (4) A chemical equilibrium aspect of the wave dynamic problem; and (5) Investigation on wave-dynamic-chemical reaction-rate coupling by means of photochemical reactions.

ABSTRACT

Oscillatory Burning Studies

Norman W. Ryan
Department of Chemical Engineering
University of Utah

Work on oscillatory burning at the University of Utah is employing a side-rented cylindrical chamber in which end-burning grains are burned. This tool, a refinement of the burner developed at the University by M.D. Horton, has the virtue of being acoustically one-dimensional, the defect of permitting only axial modes of oscillation. Versatility is sacrificed for ease of analysis.

The propellant most extensively studied is a PBAA (epoxy cure) ammonium perchlorate-copper chromite propellant (18, 80, 2 per cent) manufactured at the laboratory. The propellant manufacturing facility has a capacity of 800 gm. per batch, three to four batches per day. The immediate supervision of manufacturing by project personnel assures the necessary high degree of batch to batch uniformity.

In the present burner, the length of the gas phase in the chamber can be kept constant. The burning propellant is advanced by a hydraulically driven piston. The control system that matches the rate of piston travel to the rate of burning is actuated by a thermojunction mounted in the chamber wall. Kistler SLM pressure transducers are mounted in the piston face in contact with the base of the grain and in the end plate closing the gas space. Both mean pressure and oscillating pressure from both transducers are recorded on magnetic tape. Analysis is made from reduced-speed tape play-back.

In a series of runs at fixed gas column length, and thus at nearly fixed oscillation frequency, the ratio of pressure amplitudes is near one over most of the range of solid lengths studied, but peaks sharply at the propellant length which may be described as the resonant length matching the gas column. At solid lengths greater than this, the phase difference between gas and solid pressure signals is nearly zero, at lengths shorter it is near 180 degrees, and at lengths close to the resonant value, there is a rapid change.

The rate of growth (as measured by dlnp/dt) of the pressure signal amplitude passes through a minimum, often less than zero, as the initial length of the solid grain approaches the resonant length. When longer grains, exhibiting strong oscillations, are burned through the resonant length, the amplitudes of the oscillations diminish sharply, sometimes vanishing. In the latter case, oscillations frequently reappear as the grain burns to short-than-resonant length.

The study thus far demonstrates that the acoustics of one-dimensional, two-phase systems can be produced and quantitatively described.

PROPELLANT MECHANICAL PROPERTIES

By

Thor L. Smith
Stanford Research Institute
Menlo Park, California

ABSTRACT

Consideration will be given to mechanisms by which mechanical energy is stored and dissipated in a propellant grain subjected to stress. To describe quantitatively these mechanisms, the response to different types of stress, e.g., shear and hydrostatic, must be studied as a function of temperature, experimental time-scale, pressure, and the magnitude of the resulting strain. In addition, it should be recognized that the basic properties of a propellant usually are changed by the application of a moderately large strain, by humidity, and by aging processes. Thus, the complete characterization of propellant mechanical properties presents a number of difficult problems.

An apparatus being constructed for studying the dynamic shear modulus will be mentioned as well as the types of data that can be obtained. Currently, studies are being made of the dependence of specific volume on temperature, time, and pressure. To illustrate the effect of temperature and time on specific volume, preliminary data will be presented. Mention will be made of the possible dependence of results on the size of test specimen. The possible use of tensile data determined at various strain rates and temperatures for characterizing the time and temperature dependent propellant properties will be briefly described along with experimental difficulties associated with obtaining meaningful data.

ABSTRACT

Preliminary Measurements of the Dynamic Shear Compliance of a Solid Propellant (U)

R. C. Bryant
Atlantic Research Corporation
Alexandria, Virginia

Measurements of the dynamic shear compliance at temperatures from room temperature to 65°C and at frequencies from 25 cps to 5,000 cps will be reported. Some information on effects of aging at room temperature, aging at high temperature, moisture, stress level, and duration of stress application on the measured values of dynamic compliance will also be presented.

STATUS OF EXPERIMENTAL STUDIES OF THE SUPPRESSION OF UNSTABLE BURNING

by H. Cheung[1]
Aerojet-General Corp.

ABSTRACT

The unstable burning program at Aerojet-General encompasses the following areas of study (1) the effect of unstable burning suppression on the kinetics of chemical reactions in the vicinity of the burning surface (2) the occurrence and suppression of low frequency instability (3) the stability of deflagration of an ammonium perchlorate grain and (4) the effect of particle size on stability of combustion. Experimental data showed that aluminum oxide produces an accelerating effect on the decomposition of perchlorate acid. A propellant containing coarse oxidizer and 8% aluminum has been observed to have a high incidence of low frequency (<1000 cps) instability, and its reaction to controlled pressure disturbances will be investigated. No significant results are yet available in areas (3) and (4).

TITLE

Comparative Analysis and Interpretation of High Speed Experimental Data on Instability and Detonation Phenomena in Solid Rocket Combustion Chamber

by

F. F. Liu*
Quantum Dynamics

ABSTRACT

Some interpretation of the experimentally obtained very high speed data on dynamic combustion phenomena are presented; the results are analyzed on the context of well known theories. In order to obtain an overall appreciation of the significant regimes to which dynamic combustion phenomena may be divided, the comparative analyses are made on both the instability and detonation phenomena. These deal with the phenomenological patterns related to the initiation of instability by perturbations in the chamber, the development and generation of the harmonics, and the generation of multi-mode shock waves. Detail experimental data on the deflagration-to-detonation transitional phenomena are presented for the first time in order to illustrate an extreme case of solid propellant combustion disturbances. These works bring forth the significant revelation of time lag and relaxational phenomena which have long been suspected in theories. The existance of negative errosive coefficient and the plausible pattern of flame-gas movement in the chamber are also discussed on the context of experimental data. Efforts are also made to evaluate the degree of agreement and disagreement between existing theories and recent experimental findings.

* President and Scientific Director

Solid Propellant Rocket Combustion Instability Panel Meeting at San Francisco on March 8th and 9th, 1962

G. F. P. Trubridge
Imperial Chemical Industries Limited

Progress of Work in the United Kingdom

1. Details of programme of investigations at Sheffield University in the Department of Fuel Technology and Chemical Engineering under the control of Professor M.W. Thring and Mr. J. Swithenbank.

2. Experimental work at Rocket Propulsion Establishment, Westcott under Dr. J. Diederichsen.

3. Examples of instability which have recently arisen in the development of motors at Summerfield Research Station.

4. Status of the high frequency instrumentation and analysis work at Summerfield Research Station.

5. Determination of the dynamic modulus of solid propellants over a temperature range.

Similarity Parameters for the Prediction of

Combustion Instability

J. R. Osborn, Purdue University

Abstract

An attempt is being made to predict the initiation and amplification of combustion pressure oscillations by determining the proper correlations between a number of dimensionless groups.

Some twenty-six groups to be used in the correlations were derived from the conservation equations, the reaction rate equation, the propellant concentration distribution equation, and other equations pertinent to a gaseous flow field with an energy source. As yet the results of the analysis are incomplete.

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